The INTIFANTE'00 sea trial: preliminary source localization and ocean tomography data analysis

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Abstract— **The INTIFANTE'00 sea trial was a multidisciplinary experiment including testing of an autonomous surface vehicle, underwater communications, source localization and acoustic ocean tomography. The results shown here will concentrate on the source localization and ocean tomography data sets. The data gathered during a 24 hour run along a range independent track shows strong oceanographic features, possibly due to internal tide signature, both on the temperature data, as measured on the thermistor chain collocated with a vertical line array(VLA), and on the acoustic data. A range dependent track between 120 and 60 m water depth, shows a highly variable channel impulse response along time and range when the source was moving outwards from the VLA. In another acoustic track, the source was navigatated across a underwater canyon where the energy was rapidly distributed over a deep acoustic channel with sound trapped well below the thermocline. Good agreement between the modeled and measured channel responses represents the first step towards matched-field processing-like methods such as source localization and tracking and ocean tomography.**

Keywords— **Shallow water, source localization, ocean tomography.**

I. Introduction

Sound propagation in the ocean is highly dependent on the environmental characteristics of the propagation media between the source and the receiver. Since the oceanic environment is continuously changing in time and space, using acoustics for underwater communication and sonar detection are very challenging tasks. Conversely, the interaction between sound waves and the environment allows for retrieving environmental information from the analysis of the emitted and received signals - this is acoustic tomography [1], [2]. Therefore, being able to predict the acoustic behaviour of a given environment is the key to current advances in the usage of acoustics for ocean exploration.

In 1997, the Portuguese Foundation for Science and Technology (FCT)[1] has financed two initiatives in marine technology, namely projects INTIMATE[2] and INFANTE[3]. The former aims at developing and testing ocean tomography techniques for estimating internal tides in the continental platform. The later aims at developing autonomous underwater vehicles (AUVs) and includes a component of testing methods and algorithms for improving the capabilities of the underwater communication channel between the surface and a submerged vehicle.

The INTIFANTE'00[4] sea trial was carried out in the vicinity of Setúbal, situated approximately 50 km to the south of Lisbon, in Portugal, during the period from 9 to 29 October, 2000. The leading institutions were the Instituto Hidrográfico, that carried out the oceanographic observations and managed the research vessel NRP D. Carlos I, SiPLAB/UALG that provided the acoustic data acquisition system and the emitted source signal control and IST, that was in charge of the high frequency data communications testing. Other collaborating/participating institutions were the NATO SACLANT Undersea Research Centre with the loan of the acoustic sound source and the Ente Nazionale per l'Energia ed l'Ambiente (ENEA) that participated in the hydrological measurements.

This sea trial served a number of specific purposes under the leading projects INTIMATE and INFANTE, namely to acquire data for testing the Time-Reversal Mirror (TRM) principle for underwater communications at low-frequency (Event 1), internal tide acoustic tomography through a 25 hours observation of continous transmissions (Event 2), source localization and tracking over strong environmental variabilities, (Event 3) and over a mild range dependent environment (Event 4). The other events 5 and 6 were concernned with ocean acoustic tomography using broadband noise sources and ships of opportunity as ocean tomography source signals.

The work presented in this paper concentrates on the ocean tomography and source localization objectives over the different bottom topography conditions and with various types of emitted signals, including the noise sources.

This paper is organized as follows: section 2 gives an overview of the INTIFANTE'00 sea trial including a description of the environmental characteristics, such as bathymetry, bottom properties and hydrology, as weel as the overall experiment geometry. Section 3 describes the acoustic data gathered at the VLA and shows some forward modelling and matched-field results. Some conclusions are drawn in section 4.

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[1] Fundação para a Ciência e a Tecnologia, Ministry of Science and Technology, Portugal.

[2] "Internal Tide Measurements with Acoustic TOmography Experiments"

[3] "Development of Vehicles and Advanced Systems for Submarine Inspection"

[4] INTIFANTE is a madeup acronym from INTImate and inFANTE.

II. The INTIFANTE'00 sea trial

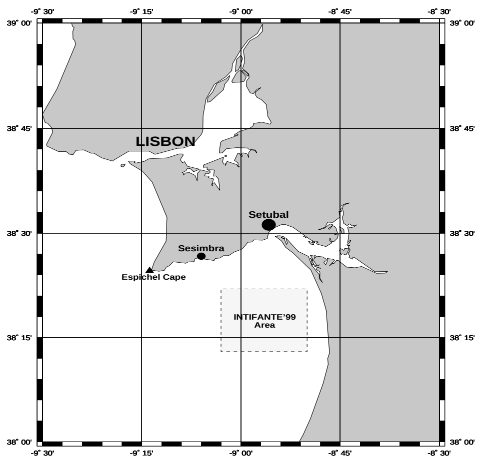

Fig. 1. *Localization of the INTIFANTE'00 experimental site*

The INTIFANTE'00 sea trial took place nearby the Peninsula of Tróia, approximately 50 km south from Lisbon in Portugal, from 9 to 29 October 2000 (see figure 1). The region is characterized by a relatively uniform continental platform with depth varying from 60 to 140 m with various bottom types, crossed by a deep underwater canyon with a steep depth variation from 120 to 500 m. The bottom topography of the area and the acoustic transmission tracks are shown in figure 2.

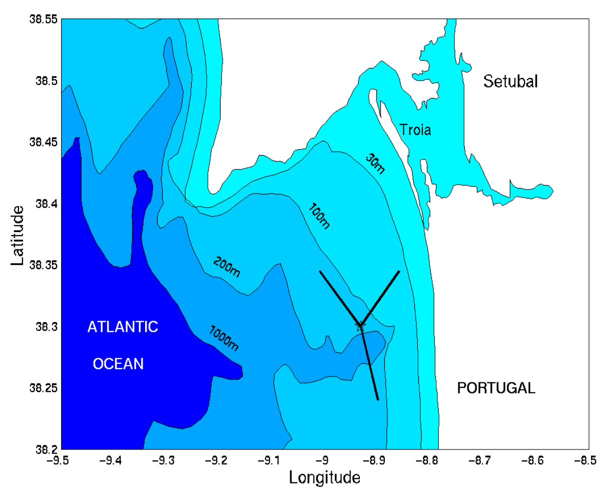

Fig. 2. *Bathymetry of the INTIFANTE'00 sea trial area, vertical line array location (◇) and acoustic tracks.*

The vertical line array (VLA) is the center of three acoustic legs along which acoustic data was trasmitted at various ranges and depths. The acoustic source ship was either stopped or moving along the tracks. The NW acoustic track is nearly range independent and parallel to the platform edge with a water depth of approximately 120 m. The NE acoustic track is perpendicular to shore and is characterized by a slow range dependency both in terms of water depth varying from 120 to 60 m and in terms of bottom characteristics that were changing from a thin sand layer to mud passing over large rock patches. The SE track is passing over a 500 m deep underwater canyon that penetrates the continental platform edge to an extent of a few kilometers. The water depth is varying from 120 to 500 m in only approximately 400 m of horizontal distance at both edges of the canyon.

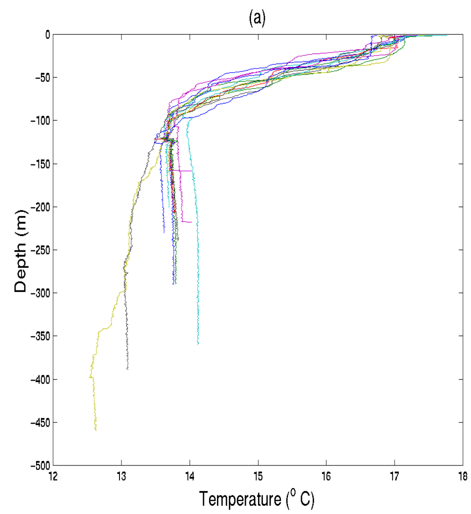

Fig. 3. *XBT temperature profiles during INTIFANTE'00.*

The XBT temperature profiles measured at various locations during the experiment are shown in figure 3. There is a strong thermocline gradient of approximately 3 °C starting at 10 m depth and extending over 50 m. Even if the temperature field is largely undersampled, a semidiurnal effect can be clearly seen from figure 4.

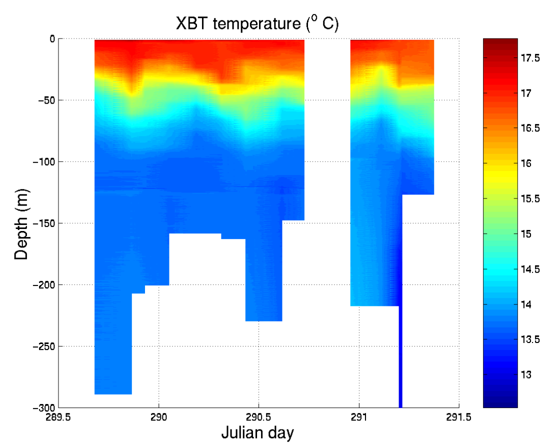

Fig. 4. *XBT temperature profiles along time during INTIFANTE'00.*

Other temperature data was recorded on the thermistor sensors colocated with the VLA. These data were transmitted and analysed online with the acoustic data on board NRP D. Carlos I. The recordings obtained during event

1 for nearly 24 hours is shown in figure 5. Despite several data interruptions due to battery change and RF transmission drop outs a clear semidiurnal pattern can be clearly noticed. Note that the time scale is oversampled while the depth sampling interval is equal to the thermistor spacing, i.e., 8 m and spans the VLA acoustic aperture.

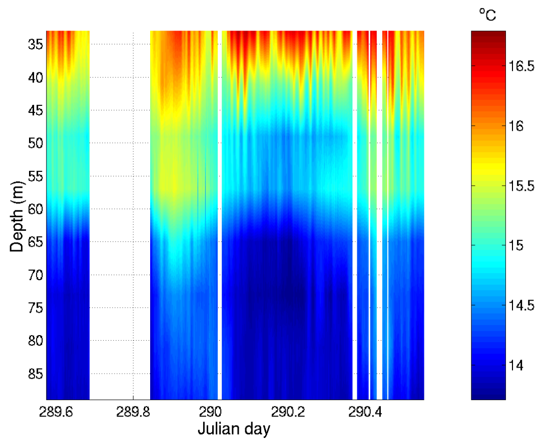

Fig. 5. *Temperature field recorded at the VLA thermistors during Event 2.*

As an overview of the technical aspects involved in the experiment, it can be referred that acoustic signals were transmitted with an HX90 acoustic projector from onboard NRP D. Carlos I and received on a moored 16 hydrophone-4m spacing VLA (see figure 6). The acoustic aperture of the VLA was located between 30 and 90 m in a 120 m water column. The acoustic signals received in the VLA were transmitted via an high-speed RF link to the research ship NRP D. Carlos I, processed, monitored and stored. Various signals were emitted by the sound projector ranging from linear frequency modulated (LFM) sweeps in the band 200-800 Hz to broadband pseudorandom noise sequences.

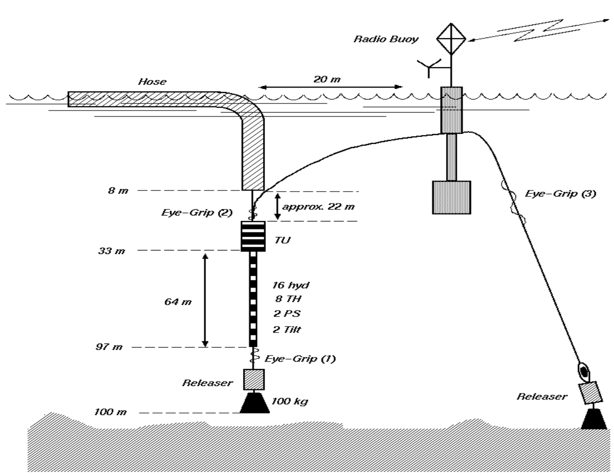

Fig. 6. *Vertical Line Array(VLA) structure.*

III. Acoustic data

A. Transmitted signals

The acoustic source power spectrum has several resonance peaks in the frequency band of interest (figure 7) which introduce a frequency dependent amplitude modulation. That frequency dependent amplitude modulation was compensated for in the transmission of the pseudorandom noise sequences (code C2) in the band 100 - 2200 Hz. The 170 and 250-800 Hz-2 second duration LFM's, codes A3 and A6 respectively, were not source spectrum compensated. During most part of the experiment the sound source was between 60 and 70 m depth.

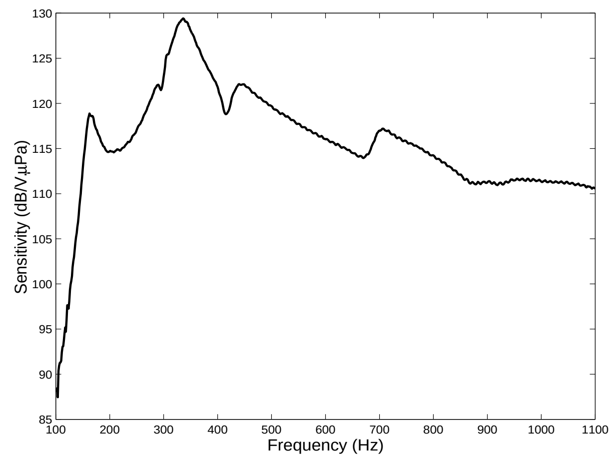

Fig. 7. *HX90 acoustic source sensitivity*

Table I contains the VLA hydrophone's depth as estimated from the top and bottom depth sensors.

TABLE I

Hydrophone array depth

Hyd. #	**Depth** (m)	**Hyd.** #	**Depth** (m)
1	32	9	64
2	36	10	68
3	40	11	72
4	44	12	76
5	48	13	80
6	52	14	84
7	56	15	88
8	60	16	92

The VLA received signals were GPS-synchronized with the emitted source signals which lead to a perfect time alignement and a very accurate estimate of the absolute travel time. This is an essential requirement for ocean tomography inversion of the water column properties.

B. Range independent NW track

The module of the matched-filtering of the received time signals with the emitted signals (pulse compression) gives an estimate of the channel impulse response and is a clear indicator of the time variability of the propagation channel. The pulse compression result for the 25 hours run along the NW range-independent track is shown in the right plot of figure 8 while the plot on the lefthandside of the same figure shows the estimated source range from the first arrival peak. Each estimated channel response is obtained from the averaging of 10 individual snapshots, which acounts for approximately 100 seconds worth of data. The pulse compressed signal plot shows a quite stable arrival pattern with arrivals separated in up to 12 resolved packets. Oscillations in the late arrivals are strongly correlated with the external (baroclinic) tide while the early arrivals packet is strongly correlated with the temperature profile variability in the water column [3].

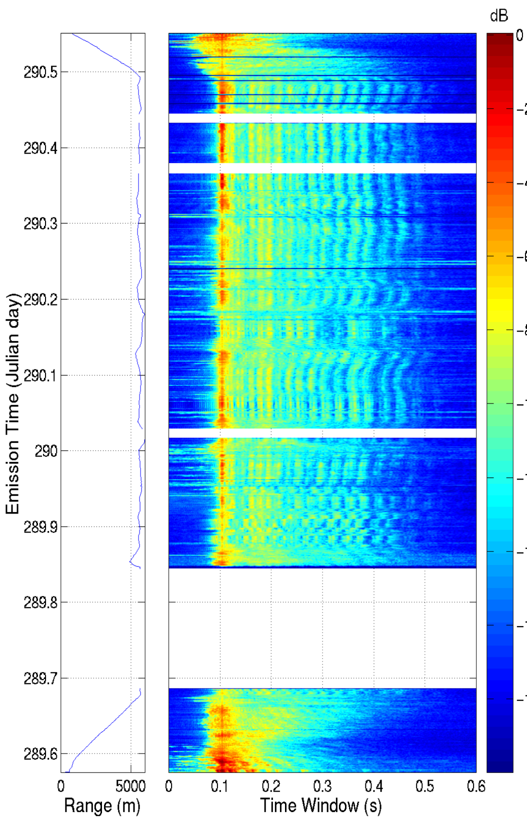

Fig. 8. *Pulse compressed arrival patterns during Event 2 with leading edge synchronization (right) and estimated source-VLA range (left).*

C. Range dependent NE track

During this track the acoustic source was first towed away from the VLA on a mild range dependent track emitting LFM codes A3 and A6, up to 5.3 km range. On the way back to the VLA along the same track the acoustic source was emitting a source spectrum compensated pseudorandom broadband noise sequence - code C2. Figure 9 shows the pulse compressed signals of the successive arrivals while the acoustic source was approaching the VLA. Possibly due to the source movement and the 100 seconds averaging the estimated channel impulse response is blurred during the middle portion of the track.

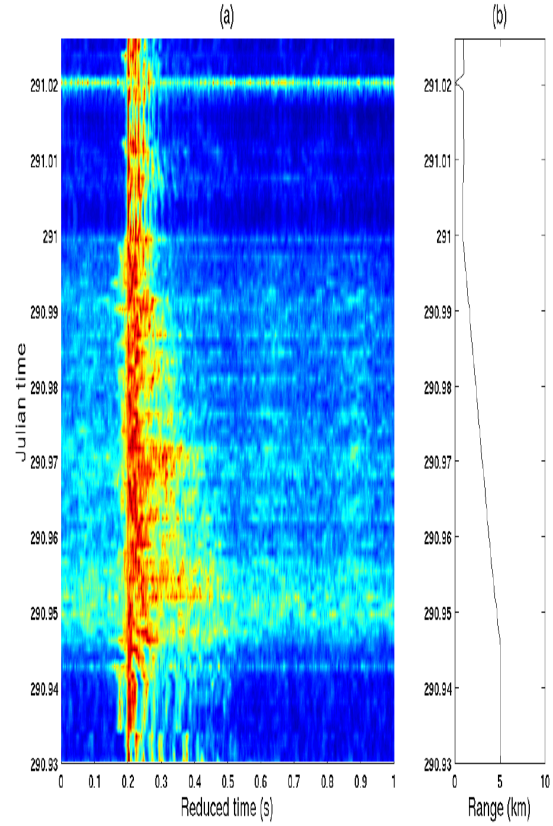

Fig. 9. *Pulse compressed arrival patterns during Event 5 with leading edge synchronization (left) and estimated source-VLA range (right).*

IV. Modelled data

A. The range independent NW track

The first objective when performing either source localization or ocean acoustic tomography is to match the received and the modeled acoustic fields. This is generally called forward modelling and represents an important - if not the most important - step towards a successful field inversion. Figure 10 represents the assumed model for the range independent NW track.

This model was used with the propagation code C-Snap [4] in a range independent mode to produce the arrival pattern shown in figure 11 as a comparison with the arrival pattern measured experimentally. It can be clearly seen that the agreement is quite good for the two curves with a clear alignement of the arrivals. This result shows that the model gives an appropriate description and a good match of the real environment, but it does not tell how that match changes through time and space.

That is presented in figure 12 that shows the correlation between the modelled and measured arrival patterns for three hydrophones and during the whole duration of the

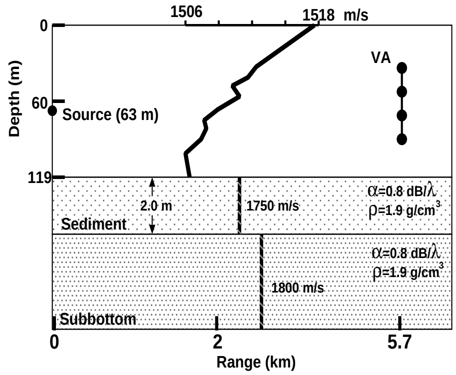

Fig. 10. *Physical model for the range independent NW track.*

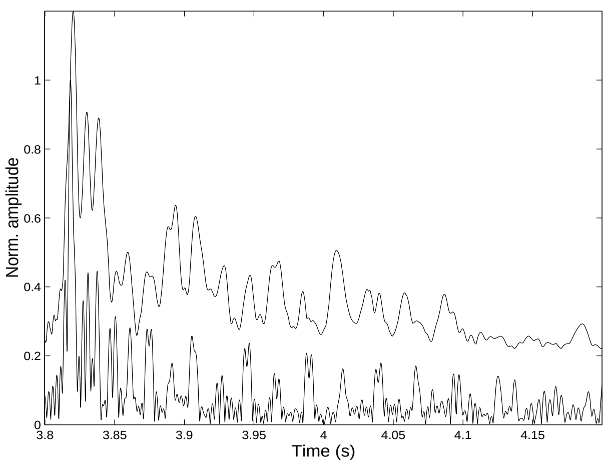

Fig. 11. *Arrival pattern during the range independent NW track on hydrophone 8 (66 m depth) at 5.2 km range: measured (bottom curve) and modelled (top curve).*

recording (20 hours). The correlation is quite high during all track with a mean value of approximately 0.8.

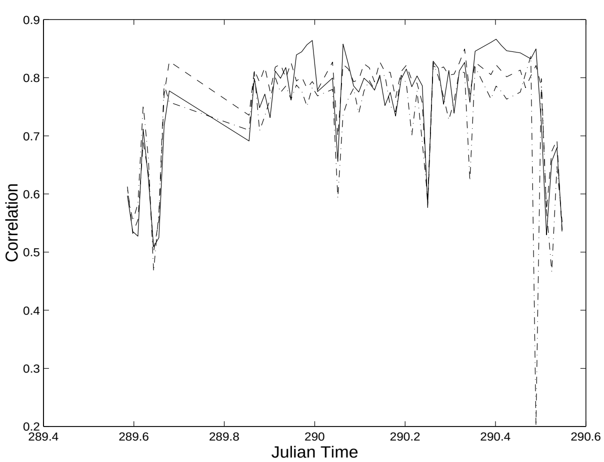

Fig. 12. *Correlation between the modelled and the measured arrival patterns along 20 hours of the range independent NW track for hydrophones 1 (top), 8 (middle) and 16 (bottom).*

B. The range dependent NE track

An attempt of forward modelling with pseudorandom noise was made for the end portion of Event 5 (shown in figure 9), while the source range was approximately 1 km and the physical model is that given in figure 10. The best attempt is shown in figure 13.

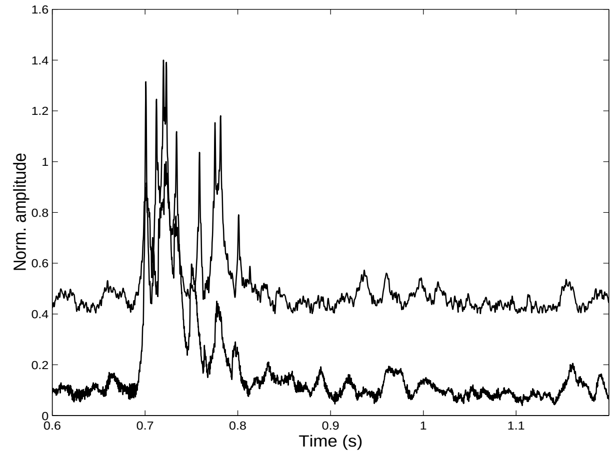

Fig. 13. *Arrival pattern during the range dependent NE track on hydrophone 1 (32 m depth) at 0.95 km range: measured (bottom curve) and modelled (top curve).*

While the source was moving at a constant range pattern around the VLA during approximately 30 minutes the correlation between the modelled arrival pattern and the data estimated arrival pattern is given in figure 14. A relatively good match was obtained even at this short range where most of the energy is concentrated on a few horizontal paths, which are most of the time unresolved and difficult to accurately estimate.

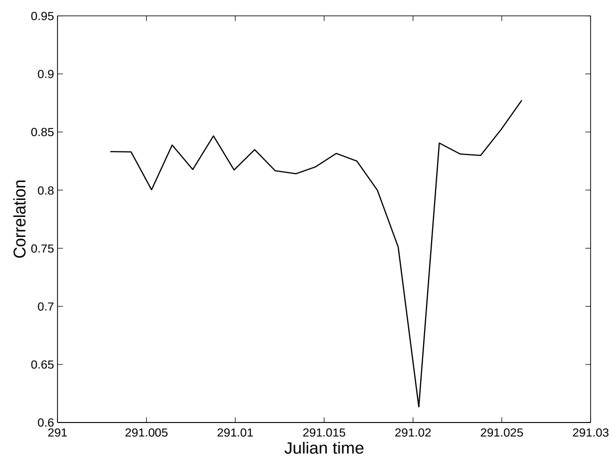

Fig. 14. *Correlation between the modelled and the measured arrival patterns along 30 minutes of the range dependent NE track for hydrophone 1.*

C. The across-canyon SE track

This propagation track represents a much more challenging problem for the acoustic model. Figure 15 shows the physical model that was used to represent the strongly range dependent propagation across the underwater canyon. The transmission loss plot across the canyon (not shown) shows that a large portion of the energy is actually sucked at the canyon border and the acoustic field structure is not reconstructed across the canyon, on the receiver side.

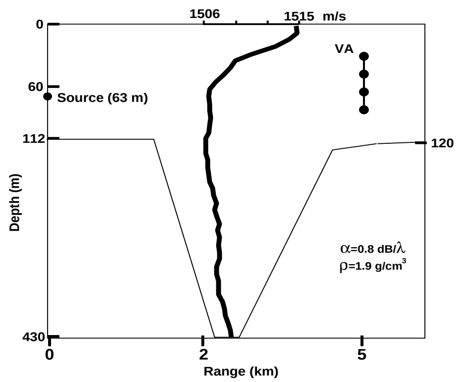

Fig. 15. *Physical model for the range dependent SE across-canyon track.*

Figure 16 shows the model predicted and the measured arrival pattern at 5 km range for hydrophone 8 located at 60 m depth. Visually the agreement is not so good as for the range independent case but represents nevertheless a correlation of approximately 0.8. The variation of that correlation along time is shown in figure 17.

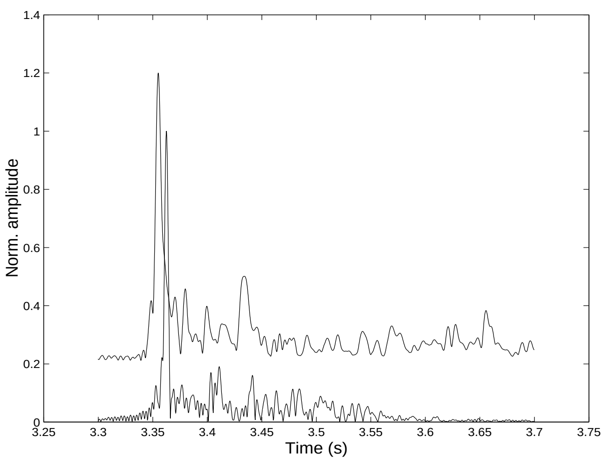

Fig. 16. *Arrival pattern during the across canyon SE track on hydrophone 8 (60 m depth) at 5 km range: measured (bottom curve) and modelled (top curve).*

V. Conclusion

The data gathered during a 24 hour run along the range independent track shows strong oceanographic features, possibly due to internal tide signature, both on the temperature data, as measured on the thermistor chain collocated with the VLA, and on the acoustic data. The range dependent track between 120 and 60 m water depth, shows a highly variable channel impulse response along time and range when the source was moving outwards from the VLA. Such strong variations are amplified during the source na-

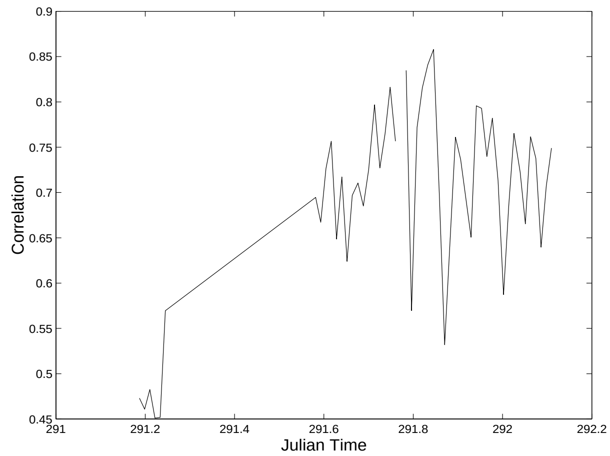

Fig. 17. *Correlation between the modelled and the measured arrival patterns along the across canyon range SE track for hydrophone 8 at 60 m depth.*

vigation over the underwater canyon where the energy was rapidly distributed over a deep acoustic channel with sound trapped well below the thermocline. Good agreement between the modelled and measured channel response on individual sensors along time was obtained for all tracks, from the range independent to the strongly range dependent, as a preliminary requirement to matched-field inversion, giving good perspectives for source localization/tracking and ocean tomography inversion.

Acknowledgment

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